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A Model for Predicting Erosion and Sediment Yield from Secondary Forest Road Construction

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One of the more visible and controversial environmental impacts associated with timber harvesting and development in central Colorado is road construction. Better tools are needed to quantify the effect of soil disturbance on erosion onsite, and the subsequent yield of sediment downstream.

This Note summarizes available data, and from this base, proposes a preliminary model for predicting an index of onsite erosion and downstream sediment yield.

Keywords: Forest roads, erosion, sediment, predictive models.

Effect of Timber Harvesting and Road Construction

Watershed erosion and damage to water quality from road construction and timber harvesting can be significantly reduced through proper planning, construction, and followup maintenance (Packer and Laycock 1969, Megahan 1972a). For example, Leaf (1970-71) showed that on Fool Creek, in the Fraser Experimental Forest, road construction associated with timber harvesting resulted in minimum erosion damage with apparently no reduction in water quality. The 3.3 miles of main access road were carefully located to avoid the stream channel and to minimize erosion. Timber was made accessible by an additional 8.8 miles of spur roads laid out along contours. Spur roads were provided with surface drainage and culverts at stream crossings. After logging was completed, spurs were seeded to grass, and culverts were removed on alternate roads to reduce traffic. Routine followup maintenance is still done on the main haul road.

Annual sediment yields were measured, using a grid of closely spaced cross sections, at the stream gages on Fool Creek and two undisturbed experimental watersheds to determine the effects of harvest cutting and road construction. These yields were based on gross volumes which included leaf litter and related organic material. Dry volumes of mineral matter therefore occupied approximately 75 percent of the total volume of debris. Samples collected from the debris basins indicated that deposited sediments contained a wide range of organic content. Using equations developed by Megahan (1972b), we estimated that organic content varied from 20 percent to less than 1 percent of the total sediment weight. The average computed organic content was approximately 1.5 percent of the total accumulated sediment weight.

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Sediment yield, including mineral soil and debris, was relatively high immediately following road construction. However, yield decreased rapidly and approached preharvest levels after 6 years despite a persistent increase in runoff caused by logging. Other studies support the time trend results observed on Fool Creek, even though soil and geologic conditions were different (Megahan 1974). It is important to understand that these conclusions apply only to **surface erosion,** and not to **mass erosion,** which can occur through the disturbance of very steep and naturally unstable topography.

Sediment Yield Model

Megahan (1974) has proposed a negative exponential equation with a linear component containing three parameters to describe the time trends in erosion discussed above. The equation can be expressed as:

$$E = \epsilon_n t + S_o(1 - e^{-kt}) \qquad [1]$$

where

- E = the cumulative onsite erosion at time (t) after disturbance,
- ϵ_n = an estimate of the long-term "normal" erosion rate on the disturbed area,
- S_o = an index of the total amount of soil available for erosion due to disturbance, and
- k = an index of the rate of decline of erosion following disturbance.

According to Megahan, (ϵ_n) is the long-term erosion "norm" which is reestablished after a site is disturbed. In some areas, this new norm may be higher than the long-term erosion under natural conditions because of irreversible changes in site factors. However, the limited data from Fool Creek and from undisturbed watersheds in the area indicate that the reestablished erosion norm on Fool Creek is essentially the same as before disturbance. Therefore, equation [1] is used to predict erosion time trends—with one modification. In this report, (ϵ_n) is defined as the natural long-term sediment yield.

The logging operation on Fool Creek required disturbance of 35 acres (Goodell 1958); virtually all of this involved construction of roads and landings. Because most of the disturbed area is occupied by roads, it can easily be described in terms of road-design variables (fig. 1). For example, 12.1 miles of road were constructed across slopes which averaged 26 percent. Thus, the 35 acres of road area corresponds to an "effective" cross section having the following characteristics:

"effective width"	= 14 ft
cut and fill slopes	= 1½:1 (33.7°)
width of disturbed area	= 23 ft
area disturbed per mile	= 2.8 acres

These results were obtained from the following equations which can be derived from figure 1:

$$D = W + \frac{W/2 \tan \rho}{\tan \Theta_F - \tan \rho} + \frac{W/2 \tan \rho}{\tan \Theta_C - \tan \rho} \qquad [2]$$

when $\Theta_F = \Theta_C = \Theta$,

$$D = W \left[1 + \frac{\tan \rho}{\tan \Theta - \tan \rho}\right] \quad D \geq W; \Theta \geq \rho \qquad [3]$$

where

- D = total disturbed length perpendicular to the centerline in ft,
- ρ = steepness of the sideslope in degrees, and
- Θ = angle of cut and fill slopes in degrees (Θ_C = angle of cut and Θ_F = angle of fill).

Equation [3] assumes balanced cut and fill (that is, that the centerline bisects the road width). This is not usually the case, since the cross section can vary from total cut to total fill in actual practice. It is assumed, however, that a sufficiently accurate index of the total area disturbed can be obtained by estimating an "effective" width and average cut and fill slopes for the proposed road system. Such estimates require considerable judgment and a knowledge of the topography.

Equation [3] provides a means for expressing the area disturbed in terms of watershed and engineering design parameters. When this expression is used in combination with equation [1] (provided that data are available), it should

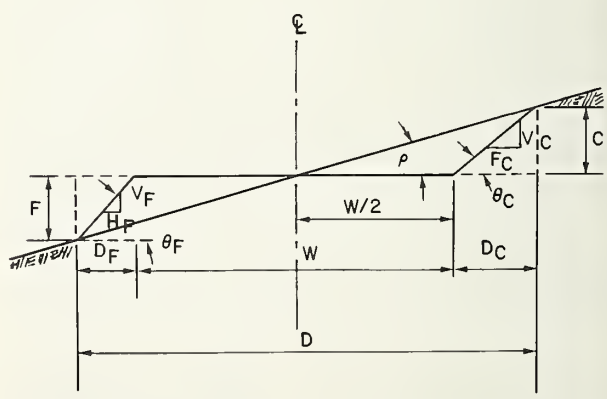

Figure 1.—Simplified cross section, illustrating design variables.

give the land use planner some latitude, subject to the limitations and assumptions discussed below, in predicting the probable erosion hazard for alternative road designs.

Onsite Erosion Versus Sediment Yield Downstream

To fit parameters to equation [1], the sediment yields measured at the gage on Fool Creek were adjusted to unit yields per acre of the area actually disturbed (35 acres). These data (summarized in table 1) represent gross volumes of mineral soil and debris immediately following road construction. It should be emphasized that table 1 summarizes erosion indices and not the actual erosion which took place on-site, since the data were collected in a debris pond at a point downstream. The accumulated erosion data were plotted in figure 2, and [1] was fitted using a nonlinear procedure:

$$E = 0.28t + 401.3(1 - e^{-0.085t}) \qquad [4]$$

E = an index of the cumulative onsite erosion in ft^3/acre at time (t) after road construction on Fool Creek,

ϵ_n = 0.28 ft^3/acre which was determined from (1) average erosion on Fool Creek after the 6th year, and (2) long-term yields from two undisturbed watersheds, and

t = the number of years after the initial disturbance.

Three assumptions were made in order to develop the model for predicting erosion and sediment yields. First, it was assumed that equation [4] provides a better index of erosion than equations based on rainfall-derived erodibility indices. Such indices do not predict time trends, and furthermore, do not account for the effects of snowmelt, which is responsible for much of the sediment yield from the densely forested subalpine zone in Central Colorado. The second assumption was that onsite erosion is proportional to the area disturbed. Finally, it was assumed that the delivery ratio is constant for a given watershed size, regardless of the amount of area disturbed. These assumptions involve complex interactions between the hydrology, geology, and soils, which need to be verified by additional study.

Based on the simplifying assumptions discussed above, equations [2] and [4] were combined in order to predict an index of the cumulative onsite erosion (S), as a function of the width of roadbed (W), average watershed sideslope (ρ), and angle of cut and fill (Θ_C and Θ_F).

Table 1.--Summary of sediment yields from Fool Creek, Fraser Experimental Forest

Year	Sediment yield[1]	Year	Sediment yield[1]	Year	Sediment yield[1]
	Ft³/acre		*Ft³/acre*		*Ft³/acre*
1952	44.9	1958	42.8	1964	([3])
1953	22.6	1959	8.6	1965	25.5
1954	([2] [3])	1960	13.9	1966	5.6
1955	([2] [3])	1961	6.1	1967	6.4
1956	36.7	1962	16.3	1968	11.1
1957	70.1	1963	([3])	1969	13.9
				1970	15.2

[1]Based on 35 acres disturbed; average dry unit weight = 85 lb/ft^3 (range: 16-120 lb/ft^3).
[2]Timber harvest.
[3]Negligible accumulation.

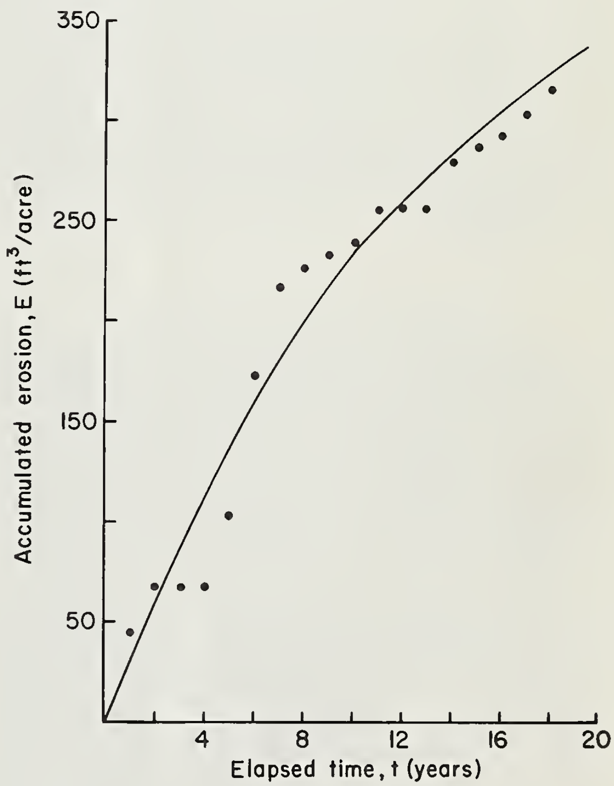

Figure 2.—Accumulated erosion as a function of time on Fool Creek, Fraser Experimental Forest.

Thus
S = 0.121 DEn

Substitution of equation [2] for (D) yields

$$S = 0.121\,WEn \left[1 + \frac{\tan \rho}{2}\left[\frac{1}{\tan \Theta_C - \tan \rho} + \frac{1}{\tan \Theta_F - \tan \rho}\right]\right] \quad [5]$$

where
S = an index of the cumulative erosion in ft^3,
E = given by equation [4],
t = the number of years after initial disturbance, and
n = the number of miles of road construction.

Because equation [5] is expressed in terms of engineering design variables, its use should provide an indication of the probable erosion impacts of alternative road systems. The yields expressed on a watershed basis are given by the equation

$$Q_S = \frac{S}{A} \quad [6]$$

where
A = the area of the watershed.

Equation [6] is valid, provided that the upstream drainage area does not exceed 1 mi^2.[2] Sediment yields at downstream points would be less, since delivery ratios are inversely related to watershed area.

Discussion and Conclusions

One of the more significant results from sediment yield studies in mountain watersheds is that most of the erosion impact occurs within a few years after disturbance. This time factor should be considered in land use planning from two standpoints: protection, and long-term effects on hydrologic parameters such as water quality.

Equations which require erodibility indices based on rainfall intensity may be grossly in error when applied to much of the subalpine zone in central Colorado, where much of the sediment yield results from melting snow. Equation [1], proposed by Megahan (1974), appears more appropriate. By describing the disturbed area in terms of watershed slope and engineering design parameters, as given in equation [5], the land use planner has some flexibility, within the limitations discussed above, in evaluating the potential impacts of various road systems.

Because the coefficients in equation [4] were developed from a very limited amount of data, they may not be generally applicable throughout the Rocky Mountain Region.[3] Nevertheless, they are based on the best information available, and should be considered as tentative estimates until more data become available.

The model described in this report is based on data obtained from a carefully constructed road system and a high standard of followup maintenance. Any application of the model should presume similar standards of construction and maintenance.

Literature Cited

Goodell, Bertram C.
1958. A preliminary report on the first year's effects of timber harvesting on water yield from a Colorado watershed. U.S. Dep. Agric. For. Serv., Rocky Mt. For. and Range Exp. Stn., Stn. Pap. 36, 12 p. Fort Collins, Colo.

Leaf, Charles F.
1970-71. Sediment yields from central Colorado snow zone. Am. Soc. Civil Eng., J. Hydraul. Div. 96(HY1):87-93. (Closure in 97(HY2):350-351.)

Megahan, Walter F.
1972a. Logging, erosion, sedimentation—are they dirty words? J. For. 70:403-407.

Megahan, Walter F.
1972b. Volume weight of reservoir sediment in forested areas. Am. Soc. Civil Eng. J. Hydraul. Div. 98(HY8):1335-1342.

Megahan, W. F.
1974. Erosion over time on severely disturbed granitic soils: A model. USDA For. Serv. Res. Pap. INT-156, 14 p.

Packer, Paul E., and W. A. Laycock.
1969. Watershed management in the United States: concepts and principles. Symp. Watershed Manage. [Lincoln College, Aug. 1969] Proc. Lincoln Pap. in Water Resour. 8:1-22.

Retzer, J. L.
1962. Soil survey of Fraser alpine area, Colorado. Soil Surv. Ser. 1956, No. 20, 47 p. U.S. Dep. Agric., For. Serv. and Soil Conserv. Serv., Colo. Agric. Exp. Stn., U.S. Gov. Print. Off.

[2] *Equation [4] is based on data collected from a 714-acre experimental watershed, and therefore applies only to drainage areas of approximately 1 mi^2 in size.*

[3] *It is worth noting here that soils on Fool Creek are uniform and derived from gneiss and schist rocks (Retzer 1962). They are deep, coarse textured, and capable of absorbing virtually all of the water during peak snowmelt.*

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